NAVAL SUBMARINE MEDICAL RESEARCH LABORATORY

SUBMARINE BASE, GROTON, CONN.

REPORT NO. 975

VISUAL CLARITY WITH A BLACK-AND-WHITE SCENE

by

James A. Worthey

Naval Medical Research and Development Command
Research Work Unit MR000.01.01-5087

Released by:

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Commanding Officer
Naval Submarine Medical Research Laboratory

30 March 1984

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SUMMARY PAGE

THE PROBLEM

A number of experiments reported over the past 15 years indicate that certain light sources provide greater "visual clarity" than others. These experiments generally involve colorful still lifes. The question presents itself whether an effect of this sort can be observed with a purely black-and-white scene.

FINDINGS

The data do not indicate a clarity effect independent of color perception. Patterns in the data of individual subjects indicate that the role of color in black-and-white vision should be studied more deeply.

APPLICATION

The negative finding of this study does not have immediate practical application. Particularly in conjunction with other more positive findings that the author has published, this work will help to understand how a person sees in well-lit environments. Such an understanding will aid in the design of lighting systems and tinted lenses.

ADMINISTRATIVE INFORMATION

This research was conducted at Indiana University School of Optometry. The writing of the paper and part of the data analysis were done at Naval Submarine Medical Research Laboratory under work unit - MR000.01.01-5087 "Under-stimulation of the red-green opponent system by fluorescent light." It was submitted for review on 29 Jan 1982, approved for publication on 4 Mar 1982, and designated as NSMRL Report No. 975.

PUBLISHED BY THE NAVAL SUBMARINE MEDICAL RESEARCH LABORATORY

ABSTRACT

Visual clarity experiments are usually done with colorful test objects, and it is generally concluded that the results of such experiments are related to the color-rendering properties of the illuminants involved. Nonetheless, it has been observed that a clarity difference between illuminants may be seen, even with black-and-white objects. An experiment was performed to measure differences of perceived clarity using only black-and-white fabric and black yarn as test objects. (The word "clarity" was not used in the instructions to subjects. They were asked questions concerning "preference" and "blackness.") The differences measured seem to indicate a role for color in black-and-white vision, but not a pure clarity effect independent of illuminant color.

INTRODUCTION

It has been observed in the illumination literature that when a person regards two similar scenes, lighted by different illuminants, they may appear to differ in "visual clarity." As summarized by Aston and Bellchambers,

> "For a given level of illumination (assuming this to be adequate for the purpose) it is generally accepted that a well-designed and balanced interior color scheme, when illuminated by fluorescent lamps giving good colour rendering, will be more attractive than the same interior illuminated by a source of poorer spectral quality. Observation has shown that the attractiveness is not due to the quality of the colour rendering of individual hues alone, but that some additional factor, variously referred to as colour or visual 'clarity', added to the attractiveness of the interior."[1]

Illumination research in the past has favored certain categories of experiments, and in particular ones involving increment threshold tasks or acuity tasks, all done with black-and-white test objects.[2] The appeal of these particular types of experiments is that they give simple, repeatable, results that covary with such independent variables as quantity of light, geometric distribution of light sources, and age of the observer. In addition, the theoretical interpretation of such experiments is relatively simple. The stimulus presentation in an increment threshold experiment, by definition, makes only a minimal departure from the condition of a uniform adapting field. Therefore, such an experiment measures "detection" without complications from "lateral interactions" or "contrast induction."

It is all very well to study intensively whatever is simple and measurable in the lighting situation. However, it is difficult to deny that an increment threshold presentation represents a great simplification of the everyday visual environment. The "real world," and in particular the outdoor environment in which man presumably has evolved, shows great nonuniformity of illumination, sharp contrasts, and bright colors. This leads to what is initially a vague question: "In the transition from the complex outdoor situation to the austere monochrome environment of an increment threshold experiment, is any potentially important stimulus parameter being ignored?" The answer to this broad question is obviously yes. Daylight is generally brighter than indoor lighting and has the unique characteristic that the diffuse light of the sky is mixed with the more yellowish, highly collimated, direct rays of the sun. The outdoor environment is generally colorful except when it is blanketed with snow. Inasmuch as the visual system responds to color and intensity, these are potentially important facts.

The question needs to be narrowed, however. A more pointed version is this: "Is there any simple but important dimension of normal human visual experience, corresponding to a quantifiable illuminant parameter,

which is systematically ignored in detection and performance experiments?" This is still an open-ended question, but it is important because lighting theories get translated into hardware, and normal visual experience is presumably what people would like to get when they pay for lighting. Visual clarity experiments address one aspect of this question.

It may be stated broadly that visual clarity experiments have given an affirmative answer to the more pointed question. They have shown that subjects consistently experience greater "clarity" with some illuminants than with others, when these are used to illuminate still lifes containing such everyday objects as "rug, draperies, clock,... fruit chain,"[3] or "a lightly polished wood panel..., a draped curtain with a floral pattern,"[1] and so forth. Unfortunately, visual clarity experiments model the complexity of everyday reality with so little simplification that they do little to isolate the dimension(s) in which visual perception is being varied. There is a need for better theoretical understanding of the visual clarity phenomenon.

An Assertation Regarding Black-and-White Test Objects

Thornton and Chen[3] have made an interesting assertion regarding visual clarity. Having shown that "prime color" lighting gives greater clarity than conventional fluorescent lighting in an orderly experiment with polychromatic still lifes, they assert without a confirming experiment that "Trained artists immediately noted the visual clarity of colorless scenes under the prime color illuminant."[3] That is, the visual clarity phenomenon seems to arise, even with a black-and-white display. The experiment I report here may be considered a test of this assertion.

A Theory to Fit the Assertion

A simple theoretical explanation may be formulated which would be consistent with the observation that illuminants can differ in visual clarity, even when the objects illuminated are purely black-and-white. The proposed theory is this: that rods - the "night vision" receptors of the retina - act as blackness receptors in moderate to high levels of illumination. This is a version of an idea put forth by Whitman Richards,[4] who theorized that rods might participate in "normalization of the lightness scale." Consider Fig. 1, which compares the sensitivities of the four receptor systems in the eye.[5] All four graphs have been scaled to a peak sensitivity of 1.0; the absolute sensitivities would, of course, depend upon the state of adaptation. From Fig. 1, it is apparent that scotopic spectral sensitivity is a function linearly independent of the other three. It fills what would otherwise be a broad gap between the spectral sensitivities of the blue-catching and green-catching cones.

It is mathematically possible, then, for an illuminant to be equivalent to a phase of daylight, or blackbody radiation, with respect to its effects on cones, and yet provide greater or lesser stimulation to rods. Under the hypothesis that rods are blackness

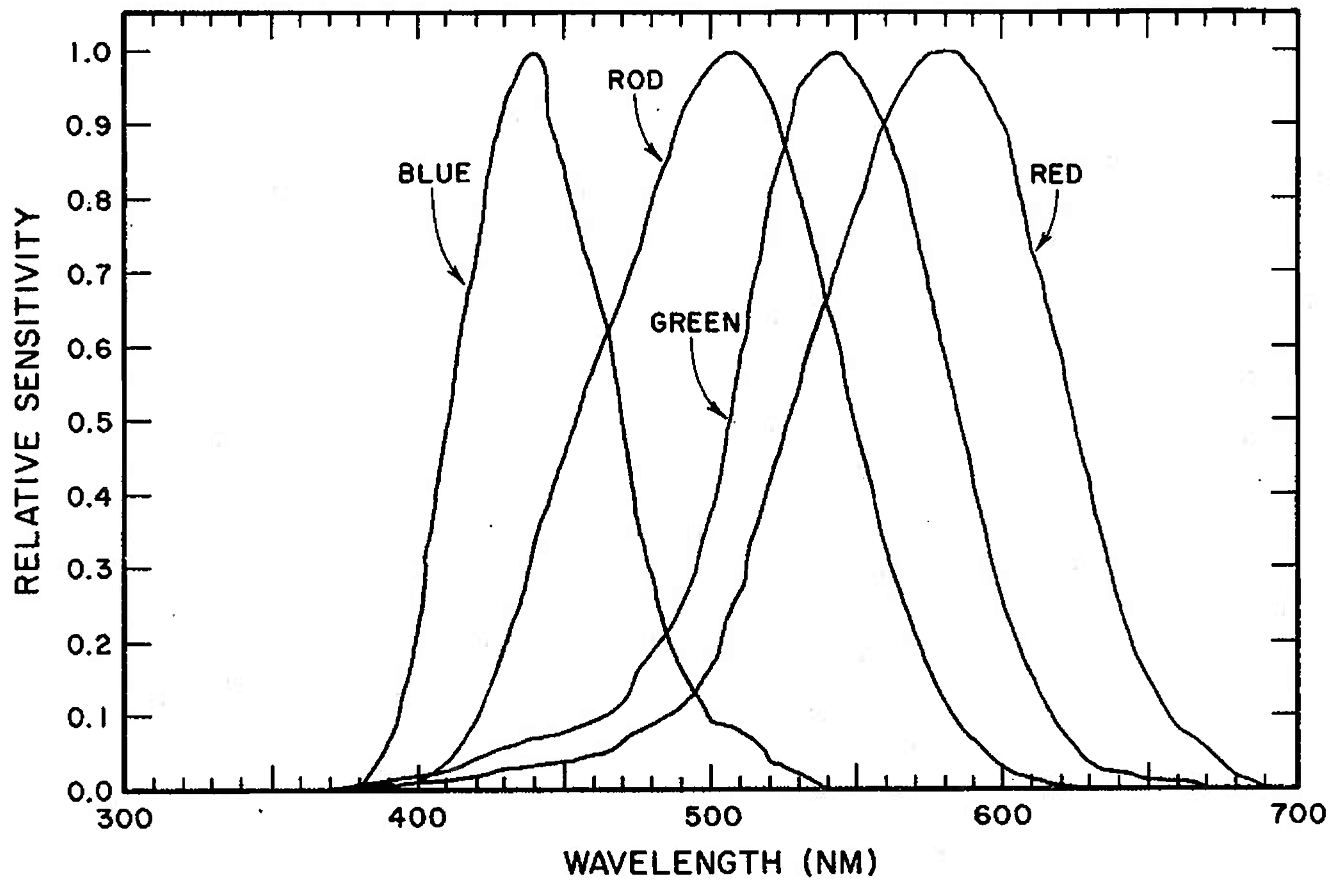

Figure 1. Relative sensitivities of the rod system and three cone system. The rod curve is the CIE's V'_{λ}, while the cone curves are psychophysical data of Wald.[5]

receptors, then, relative differences in rod stimulation would cause blacks to appear darker or lighter. In particular, if two illuminants were compared which differed only in relative rod stimulation, objects might appear washed out, or lacking in clarity, under the lights that stimulated rods less.

Common illuminants do in fact differ considerably in the degree to which they stimulate rods. Figure 2 shows relative rod stimulation for many common illuminants. The standard of scotopic stimulation used is natural daylight as represented by the model of Judd, MacAdam and Wyszecki.[6] Since most of the normal spectral variation of daylight can be described as variation in color temperature, the data are plotted with color temperature as the independent variable. (It was necessary to extrapolate the daylight model to low color temperatures.) Table I gives the codes by which the illuminants are identified. Figure 3 of Reference 7 confirms the rather well-known fact that chromaticities of most illuminants plot near to the blackbody locus in the CIE chromaticity chart. We may conclude, then, that many common vapor discharge lights are similar to daylight in color, but lower in their relative stimulation of rods.

Figure 2 provides the basis of an experiment to test whether greater rod stimulation can improve the clarity of a black-and-white scene. It is not possible to pick out two lamps which affect cones identically (meaning that they are metamers), but differ in their effect on rods. It is possible to design an experiment with commercial lamps in which color temperature and relative rod stimulation both act as independent variables. Then the data can be analyzed to test whether the subject's responses depend on both independent variables, or one, or none.

It will be seen below that the data do not support the hypothesis that rods act as blackness receptors. The data do, however, provide help in understanding the observation of Thornton and Chen.[3]

APPARATUS AND METHOD

The subjects looked into two independently lighted chambers, separated by a thin partition. Each chamber measured 30 x 60 x 49 cm, and was open on the 60 x 30 cm end. The ceiling of each chamber consisted of a tracing-paper diffuser. Above this was an attenuator, consisting of a sheet of tracing paper covered over much of its surface by bits of black tape. The left-hand attenuator was rolled and unrolled manually during set-up, and secured with paper clips. The right-hand attenuator had a stepping-motor drive so that it could be adjusted by the subject. All the walls of the viewing chambers as well as those of the lamp chambers above the diffusers were painted with a matte finish latex base "pure white" paint. Considerable time was spent adding layers of paint and otherwise eliminating sources of color differences between the two sides of the apparatus. If the same type of fluorescent tube was put in both sides, a perceptible color difference would sometimes remain, but it was quite small.

TABLE I. Identification of Illuminants in Figure 2

Symbol	Illuminant
Conventional fluorescent lamps	
WMWT	Warm white fluorescent
SFTW	Soft white fluorescent
CLWT	Cool white fluorescent
DLGT	Daylight fluorescent
Fluorescent lamps for which special claims of clear seeing or comfort are made	
ULT3	3000-K Ultralume
ULT41	4100-K Ultralume
ULT5	5000-K Ultralume
VITA	Vita-Lite fluorescent
VLUX	Verilux fluorescent
Other vapor discharge illuminants	
HPNA	High pressure sodium vapor light
HPMVD	High pressure mercury vapor light

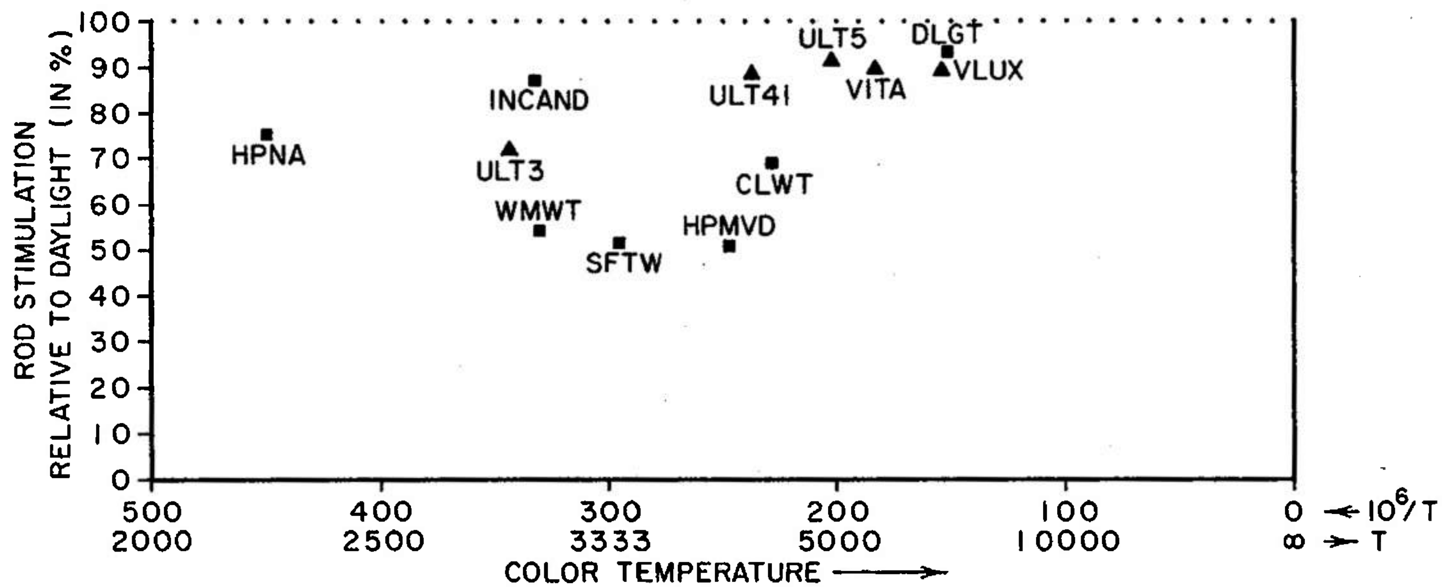

Figure 2. Relative rod stimulation for some common illuminants, plotted against color temperature. The standard of 100% scotopic stimulation is natural daylight as represented by the model of Judd, MacAdam, and Wyszecki.[6] Squares represent common artificial illuminants. Triangles represent lights for which special claims of clear seeing or health benefits are made. The codes identifying the points are decoded in Table I.

The choice of objects for subjects to look at presented some difficulty. I wished to use black-and-white objects and yet give the subjects some basis for preferring one side over the other. Pilot experiments showed that if black-and-white printing or photos were the objects of regard, subjects had difficulty expressing a preference for one light source over another; on the working assumption that rods affect the normalization of the lightness scale, this was reasonable, since printing and photographs necessarily incorporate an arbitrary lightness adjustment. The objects finally selected were bows of black ornamental yarn, and rectangles of cloth with a black-and-white woven-in checherboard pattern. The fabric, a polyester-cotton blend, was never washed. Inspection with a blacklight showed little or no fluorescence, so the cloth was free of optical brighteners. The rectangles of cloth were cut and hemmed to mirror-image appearance, and one crease was ironed into each. They were laid on black construction-paper rectangles of about the same size to prevent the white surface from "shining through." The result was two very similar monochrome displays, free of obvious color contrasts, but having some subtle and fine visual detail. It was possible for a subject to prefer one lighting type over another on the basis that it somehow better revealed the detail.

Figure 3 is a photograph showing the approximate appearance of the apparatus as seen by the subject. For "near" observations, a stool was provided near the apparatus which permitted the subject to lean forward into the viewing chambers. For "far" observations, the subjects stood about three meters from the test objects. The "near" condition was intended to simulate the full-field stimulation of working in a well-lit room. The "far" condition was intended to simulate the low-glare foveal viewing conditions common to many vision experiments.

Procedure

Five light sources were used: Incandescent, Warm White, Cool White, Ultralume 3000, and Ultralume 4100. The possible combinations of five types comprise a matrix of 25 pairings. Only the incandescent-incandescent pairing was omitted. The other pairings of like with like were included as a check for gross asymmetry in the apparatus, and pairings which differed only by the exchange of left and right lights were retained as a way to add redundancy and compensate for residual left-right asymmetry.

For each of the 24 lighting conditions, each subject (1) Set the luminance on the right to match that on the left. Specifically, the subject was asked to make a brightness match based on white areas of the chamber wall and floor, away from the test objects. (2) Sat very near the apparatus; inspected the objects by leaning into one chamber and then the other; and then responded to these questions:

(a) On which side do you prefer the lighting for looking at these objects?

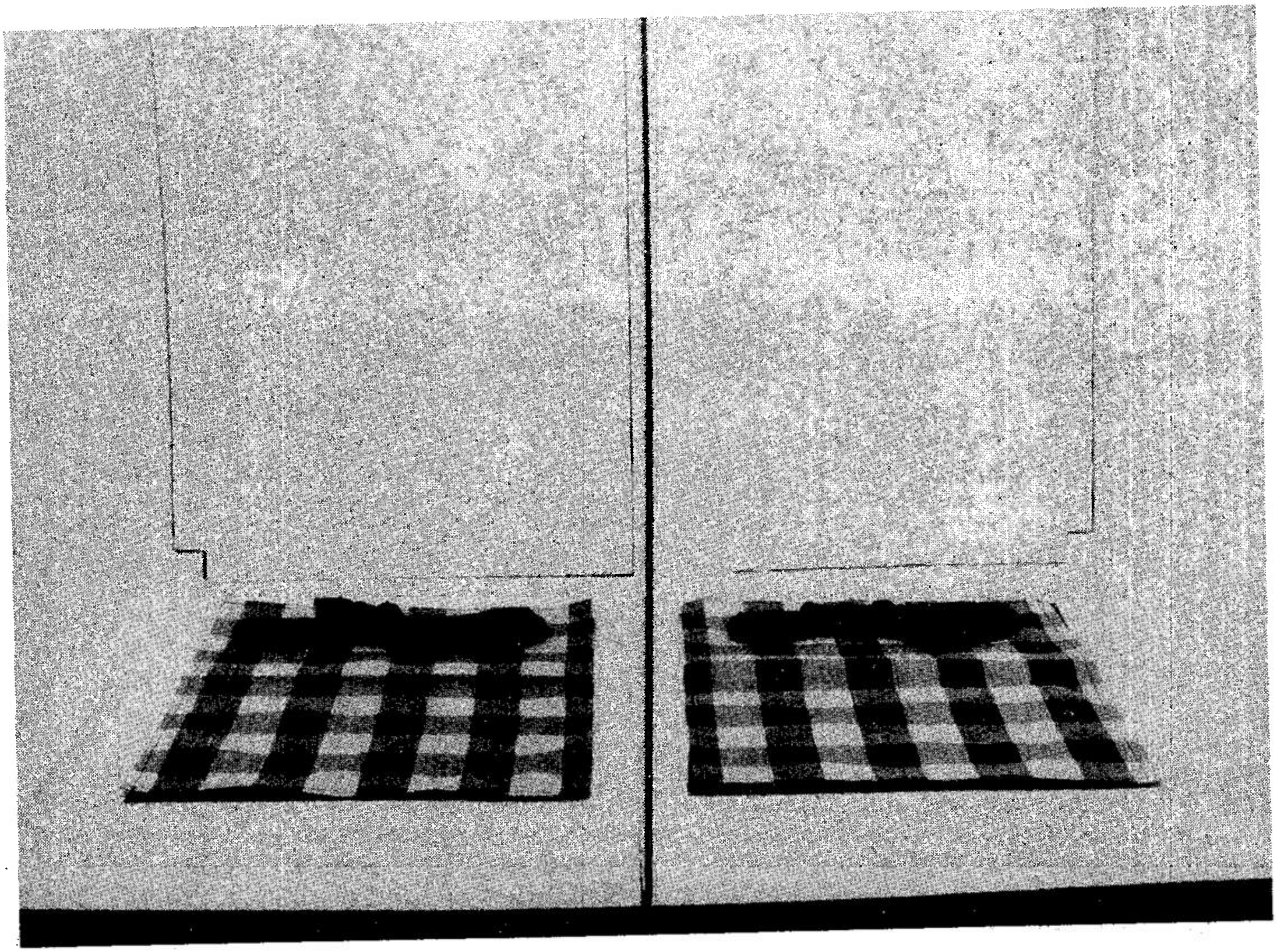

Figure 3. Approximate appearance of the apparatus as seen by the subject.

(b) On which side do the blacks appear blacker?

(3) Moved back to a position about three meters from the objects and then answered the same two questions.

Subjects were required to answer each question by "left" or "right," modified by "maybe" or "definitely." In the course of reading the instructions aloud, the experimenter handed the subject a piece of paper which said "definitely left", and "maybe left" on the left-hand side and "definitely right" and "maybe right" on the right-hand side. The object here was to spell out the choices clearly and to head off any possible laterality confusion.

The subject's oral responses were recorded as number n_{ij} according to the code: -2 = "definitely left," -1 = "maybe left," +1 = "maybe right," +2 = "definitely right." Thus each subject gave an array of 96 numbers.

Subjects

Five men and three women, ranging in age from 26 to 37 (median age 31) participated as subjects. Subjects requiring corrective lenses wore their accustomed untinted spectacles.

RESULTS: Pooled Data

The simplest result, independent of any theoretical assumptions, would be that most subjects were consistent in their responses for most of the pairings. This was not the case, as indicated by the data summed over subjects (Table II). As the range of possible values in Table II is -32 to +32, we may conclude that no strong effect, consistent across subjects, was observed.

I have also analyzed each subject's data for dependency on illuminant color or relative rod stimulation. Again, the simple "visual clarity" hypothesis is not confirmed, but certain patterns do emerge.

Bivariate Analysis: Background

As stated above, two independent variables may in some likelihood have affected the data: Color temperature and relative rod stimulation. (Should the reader object *a priori* to rod stimulation as an important variable, "prime color content" or some other measure of difference may be substituted with little change in the sense of what follows.) The results must be interpreted carefully, owing to the particular combinations of the independent variables that were used. An ideal confirmation of the hypothesis would occur if a subject always preferred the higher color temperature when the colors were different, such as INCAND vs ULT41, but consistnetly chose the higher rod stimulation when the colors were nearly the same, such as ULT41 vs CLWT. Then rod stimulation would appear to be important and not confounded by the color effect. No subjects gave this clear confirmation of the hypothesis.

Alternatively, a subject could always choose the lower color temperature. In this case, the rod effect may be there, but if so, it is confounded by the color effect.

TABLE II. Raw Data Summed over Subjects. Each number in the Table is the score the first illuminant received when compared to the second. A positive score indicates that the first light was preferred to the second, or that it gave blacker blacks. As the scores have been summed over eight subjects, and two repetitions per subject, the range of possible results is -32 to +32. The pairings are given with the light of lower color temperature first.

Conditions	Near		Far	
	Preference	Blackness	Preference	Blackness
INCAND vs WW	1	3	-1	-11
INCAND vs CLWT	-4	-3	0	-7
ULT3 vs INCAND	1	2	1	12
INCAND vs ULT41	4	4	3	-2
WMWT vs CLWT	8	6	7	-2
ULT3 vs WMWT	-1	-3	-10	-13
WMWT vs ULT41	11	-7	9	-7
ULT3 vs CLWT	7	1	3	-2
ULT41 vs CLWT	-1	8	2	7
ULT3 vs ULT41	17	4	0	-3

Two subjects, (CW and TT) clearly fit this pattern for nearly all of their responses.

If a subject almost always chose the higher color temperature, this could mean that the rod effect was either non-existent, weak, or opposite in sign to that originally hypothesized. One subject (EO) showed essentially this pattern.

As another extreme, a subject could give essentially random data, indicating that lighting did not govern "blackness" or "preference" for this person in this situation. If all subjects gave random responses, it would tend to indicate a poor experiment with important variables not being sufficiently controlled. No subject gave wholly random data, as will be seen below.

Bivariate Analysis: Results

The array of numerical responses for each subject was used to test hypotheses of this algebraic form

$$P = B_o + B_t \Delta T + B_r \Delta R \qquad (1)$$

where P = numerical responses as to preference or blackness,
ΔT = difference in color temperature between the two sides,
ΔR = difference in percent rod stimulation,
B_o, B_t, B_r = parameters to be fit to the data.

With this general form of hypothesis, we may distinguish four possibilities of interest (Table III). Each of these possibilities may be tested for statistical significance, using an F-test. Significance for version (1) or (4) of the hypothesis would support the original supposition concerning rods. Significance for any of the hypotheses at least supports the idea that the questions had some meaning for the subjects.

Were the data in fact consistent across subjects, the numerical quantities B_o, B_t, and B_r would be of interest. Since such consistency was lacking, I present in Table IV only a summary which shows the pattern of responses for each subject.

We may conclude from Table IV that the questions were far from meaningless to the subjects. Subjects CLW and TT, for instance, consistently see blacks as blacker under the illuminant of lower color temperature, and they prefer the lower color temperature with great consistency. For EO, color predicts blackness, but not preference.

The possibility that the judgments contain some systematic dependency on "percent rod stimulation" cannot be ruled out. The liberal scattering of statistical significant results in columns 1 and 4 may indicate a rod effect or a color rendering effect, or it may well be only an artifact of the systematic relationship between the independent variables. We cannot decide these possibilities, but we can state that the simple rod effect sought is weak, or non-existent.

Clarity with a Black-and-White Scene

Regarding the question, whether "visual clarity" differences between illuminants may arise with black-and-white test objects, it appears that this may be a matter of interpretation.

TABLE III. Four statistically testable versions of the hypothesis expressed in Equation (1).

(1) That the dependency on ΔR can by itself account for the data ($B_t=0$).

(2) That ΔT alone suffices to fit the data ($B_r=0$)

(3) That ΔT and ΔR taken together provide a fit ($B_r \neq 0$ and $B_c \neq 0$).

(4) That after the dependency on ΔT is accounted for, the ΔR term can improve the fit.

TABLE IV. Response Patterns of the Eight Subjects who Completed the Experiment. The subjects repeatedly responded to four questions: NP = "Which side do you prefer," asked at near; NB = "On which side do the blacks look blacker," asked at near; and FP, FB = same questions asked at far. Four versions of the regression hypothesis (Eq. (1)) were tested, as listed in Table II. The four by four array for each subject indicates whether the responses to each question were explained by each version of the hypothesis.

Question	Form of hypothesis 1	2	3	4	Question	Form of hypothesis 1	2	3	4
Subj: JM					Subj: MG				
NP		-			NP	-		+	-
NB		-	-		NB		+	+	-
FP	-	-	-	-	FP		+	+	-
FB					FB		+	+	
Subj: CLW					Subj: EO				
NP		-*	-*	+	NP			+	-
NB		-*	-*	+	NB		+	+	
FP		-*	-*		FP		+*	+*	
FB		-*	-*		FB				
Subj: CAW					Subj: TT				
NP					NP		-*	-*	+
NB		+	+		NB		-*	-*	+
FP		-	-		FP		-*	-*	
FB					FB		-*	-*	
Subj: AT					Subj: EM				
NP					NP				
NB	+		-	+	NB		+		
FP					FP	-		+	-
FB		+*	+*		FB				

A blank indicates significance poorer than 5%. A + or - indicates significance at the 5% level. In columns 1 and 4, the sign indicates the sign of B_r; a plus sign means that greater rod stimulation was preferred (or gave blacker blacks). In columns 2 and 3, the + or - indicates the sign of B_t; a plus sign means that higher color temperature was preferred (or gave blacker blacks). A +* or -* indicates statistical significance at the 0.1% level.

If one seeks a clarity effect wholly independent of color perception, then the present data indicate that such an effect is weak or non-existent. If two illuminants compared in an experiment differ in color, however, then the data indicate that a clarity effect may be expected on that basis alone. Alternatively, if "black-and-white" is taken to include off-white backgrounds such as newsprint, and if two illuminants are compared which differ in their rendering of the off-white, then again a color difference could underlie a clarity difference. The present data do not wholly rule out a "pure" clarity effect with monochrome objects, but they suggest that the role of color in black-and-white vision may have greater importance. This could perhaps be studied directly in simple experiments.

ACKNOWLEDGMENTS

The data reported here were taken while the author was a graduate student in the Physiological Optics Program, School of Optometry, Indiana University, Bloomington, Indiana. Financial support came from the American Optometric Foundation, and from the author's wife, Carol. The fluorescent tubes were donated by Westinghouse Electric Corporation. The paper was written while the author was a National Research Council research associate at the Naval Submarine Medical Research Laboratory.

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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER: NSMRL Report No. 975	2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle): VISUAL CLARITY WITH A BLACK-AND-WHITE SCENE	5. TYPE OF REPORT & PERIOD COVERED: Interium report
	6. PERFORMING ORG. REPORT NUMBER: NSMRL Report 975
7. AUTHOR(s): JAMES A. WORTHEY	8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Naval Submarine Medical Research Laboratory, Naval Submarine Base New London, Groton, CT 06349	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 61152N, MR000.01.01-5087
11. CONTROLLING OFFICE NAME AND ADDRESS: Naval Submarine Medical Research Laboratory, Naval Submarine Base New London, Groton, CT 06349	12. REPORT DATE: 30 March 1984
	13. NUMBER OF PAGES: 14
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): Naval Medical Research and Development Command, Naval Medical Command, National Capital Region, Bethesda, MD 20814	15. SECURITY CLASS. (of this report): UNCLASSIFIED
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

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17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

fluorescent bulbs; visual clarity; black-and-white scene; color-rendering

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Visual clarity experiments are usually done with colorful test objects, and it is generally concluded that the results of such experiments are related to the color-rendering properties of the illuminants involved. Nonetheless, it has been observed that a clarity difference between illuminants may be seen, even with black-and-white objects. An experiment was performed to measure differences of perceived clarity using only black-and-white fabric and black yarn as test objects. (The word "clarity" was not used in the

20. continued:

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